VIRTUAL TELEPRESENCE FOR THE FUTURE OF ROV TELEOPERATIONS: OPPORTUNITIES AND CHALLENGES

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ABSTRACT

Underwater robots, including Remote Operating Vehicles (ROV) and Autonomous Underwater Vehicles (AUV), are currently used to support underwater missions that are either impossible or too risky to be performed by manned systems. In recent years the academia and robotic industry have paved paths for tackling technical challenges for ROV/AUV operations. The level of intelligence of ROV/AUV has increased dramatically because of the recent advances in low-power-consumption embedded computing devices and machine intelligence (e.g., AI). Nonetheless, operating precisely underwater is still extremely challenging to minimize human intervention due to the inherent challenges and uncertainties associated with the underwater environments. Proximity operations, especially those requiring precise manipulation, are still carried out by ROV systems that are fully *controlled by a human pilot. A workplace-ready and worker-friendly ROV interface that properly simplifies operator control and increases remote operation confidence is the central challenge for the wide adaptation of ROVs.*

This paper examines the recent advances of virtual telepresence technologies as a solution for lowering the barriers to the human-in-the-loop ROV teleoperation. Virtual telepresence refers to Virtual Reality (VR) related technologies that help a user to feel that they were in a hazardous situation without being present at the actual location. We present a pilot system of using a VR-based sensory simulator to convert ROV sensor data into human-perceivable sensations (e.g., haptics). Building on a cloud server for real-time rendering in VR, a less trained operator could possibly operate a remote ROV thousand miles away without losing the minimum situational awareness. The system is expected to enable an intensive human engagement on ROV teleoperation, augmenting abilities for maneuvering and navigating ROV in unknown and less explored subsea regions and works. This paper also discusses the opportunities and challenges of this technology for ad hoc training, workforce preparation, and safety in the future maritime industry. We expect that lessons learned from our work can help democratize human presence in future subsea engineering works, by accommodating human needs and limitations to lower the entrance barrier.

Keywords: ROV, Virtual Reality, Telepresence

INTRODUCTION

Augmenting human abilities in subsea engineering, such as offshore construction and inspection (e.g., floating cities and offshore wind farms) and subsea exploration and operations (e.g., offshore mining, subsea cables, and energy harvesting), provides a historic opportunity for the new economic growth and scientific discoveries [1]. Underwater infrastructure is also critical to tackling the unprecedented challenge of the climate crisis - various disaster models project a 45-87% increase of severe hurricanes in the next three decades in the US coastal areas [2], threatening more than 30% of the US population [3]. There is an urgent need to transform the future workforce partnering with new subsea robot technologies to meet the societal, environmental, and engineering needs of grand significance.

Subsea engineering remains a highly specialized area with a high barrier for broader participation. Most subsea jobs require a strict professional preparation (science, engineering, and diving knowledge) that takes many years of training. The existing subsea workforce consists of marine engineers, professional divers, and robot service providers, and only a small portion holds licenses for certain tasks. But the current subsea professionals may not possess all the needed knowledge from other domains such as structural engineering knowledge. This high barrier of subsea works has substantially limited the workforce for an aggressive human ocean exploration roadmap. The future subsea engineering should be participatory, meaning that the majority of the interested populations should not experience serious difficulties in entering a subsea career.

The realization of this goal depends heavily on the efficient utilization of underwater robots such as Remote Operating Vehicles (ROV) and Autonomous Underwater Vehicles (AUV) as remote surrogates for future subsea workers. However, the harsh subsea environment and difficult robot controls are major obstacles for the future subsea workforce to utilize or team up with underwater robots. Underwater robot operations are particularly challenged by the uncertainties of the subsea environments, including the low visibility, chaotic ocean currents, interference from subsea ecosystems, and less understood subsea properties of materials and systems [4]. Existing Human-Robot Collaboration (HRC) methods for land applications are insufficient and not directly applicable to meet the unique challenges of subsea engineering. There is also little knowledge about the implications of subsea engineering operations in human perception, training, education and health, such as work-related stress, sensory loads and fear of being underwater [5].

To fill the gap in ROV operations, our team proposes a new Virtual Reality (VR) based teleoperation approach called "Human-Robot Sensory Transfer", which transfers and simulates robot sensor data of subsea workplaces as human-perceivable multimodal sensory feedback, including visual, tactile, haptics, and force feedback to enable a shared perception in complex subsea workplaces. In the remainder of this paper, we will discuss the basics of the proposed method, and its potential challenges and opportunities.

METHODOLOGY

1. Problem Related to ROV Operations

Underwater robots currently are used to support underwater missions that are either impossible or too risky to be performed by manned systems. The original design philosophy of ROV was driven by automation for replacing humans in repetitive or dangerous subsea works. In recent years the academia and robotic industry have paved paths for tackling technical challenges for autonomous ROV such as underwater manipulation [6], power supplies [7] and data telecommunication networks [8]. The level of intelligence of ROV has increased dramatically as a result of the recent advances in low-power-consumption embedded computing devices and machine intelligence [9]. Nonetheless, operating precisely underwater is still extremely challenging to achieve for a fully autonomous system due to the inherent challenges associated with the underwater environments [10]. As a result, close-range operations, especially those requiring manipulation, are still carried out by ROV systems that are fully controlled by a human pilot. A workplace-ready and worker-friendly ROV interface that properly simplifies control and increases remote operation confidence is the central challenge for the wide adaptation of ROVs.

Compared to the ROV automation solutions, the technical specifications for human-in-the-loop challenges are less thought out. Established algorithms, methods, and systems for automation are not effective for supporting tasks with an intensive human engagement, such as overwhelming information for underwater environmental understanding; difficulty of remote robot controls, the missing sensations of human operators underwater (e.g., inability to directly sense water flow), and maneuver and navigation in unknown and less explored subsea regions and works. To democratize human presence in the future subsea engineering works, a new design paradigm for ROV that accommodates human needs and limitations are needed to lower the entrance barrier. The technical innovation should also meet the requirements for new subsea jobs and technology certification.

Our team is funded by National Science Foundation (NSF) to design and explore *Human-Robot Sensory Transfer*, a new Human-Underwater Robot Interaction method based on the virtual telepresence and sensory augmentation technologies, to significantly lower the barrier for underwater robot operations. We envision that the human-robot sensory transfer method to be *virtual*, in which the solutions are based on a Cloud infrastructure where human agents located at different locations can access multiple underwater robots remotely. The multimodal sensory augmentation in an immersive virtual environment will enable an "idiot-proof", intuitive teleoperation experience with minimum training needs. We also expect the method to be *ad hoc*, meaning that the resources (human and robots) can be easily matched and rematched, and the work schedule is adaptive, etc. The following section describes our approach.

2. The Proposal Human-Robot Sensory Transfer Method for ROV Teleoperation

Fig.1 illustrates the architecture of the proposed human-robot sensory transfer system for simplifying ROV teleoperation. The proposed system consists of five modules, including *underwater robot (ROV)*, *subsea sensing*, *workplace model*, *robotic simulation*, and *human operator*. The details of each module are described as follows.

- **Subsea Sensing Module**: Subsea workplaces will be substantially different from our established workplaces, and thus the human operator may not perceive the environmental data in a desired way. As a result, we expect the sensing system to capture the key characteristics of a dynamic underwater environment for sensory augmentation. Subsea sensing module builds on a multi-level sensor network to collect real-time subsea environmental data pertaining to the hydrodynamic features and temperature changes. The sensor network captures three levels of sensor data to meet the sensing needs, including *far field hydrodynamic status* based on an acoustic Doppler current profiler (ADCP) [11] to collect underwater wave profiles in the 3 meter-20 meter proximity; and *near field* (0.1 meter – 3 meter) and *micro field* (<0.1 meter) turbulence based on *in-situ* sensors equipped on the ROV. The far field sensing aims to identify the sudden change of underwater wave in a bigger scale, or the so-called "seamount" (Fig.1). The existence of seamounts often poses significant risks to the teleoperation of ROV as they usually intensify the tidal flow and water stratification, interrupting the on-gong ROV operation profiles. As for the in-situ sensor, we leverage an *artificial skin* – an innovative distributed sensor system that allows a flexible add-on sensor package. The artificial skin sensing system enables fast disturbance detection and rejection to improve vehicle control accuracy. The design of the in-situ sensor is based on our pervious works [12-14] on lateral-line sensory mechanism within fish which consists of specialized "hair-cells" throughout the body surface capable of detecting pressure gradients and shear stress. Sensing signals include temperature, pressure gradient, and shear stress sensors distributed throughout a custom shell designed to fit to the surface of the ROV.

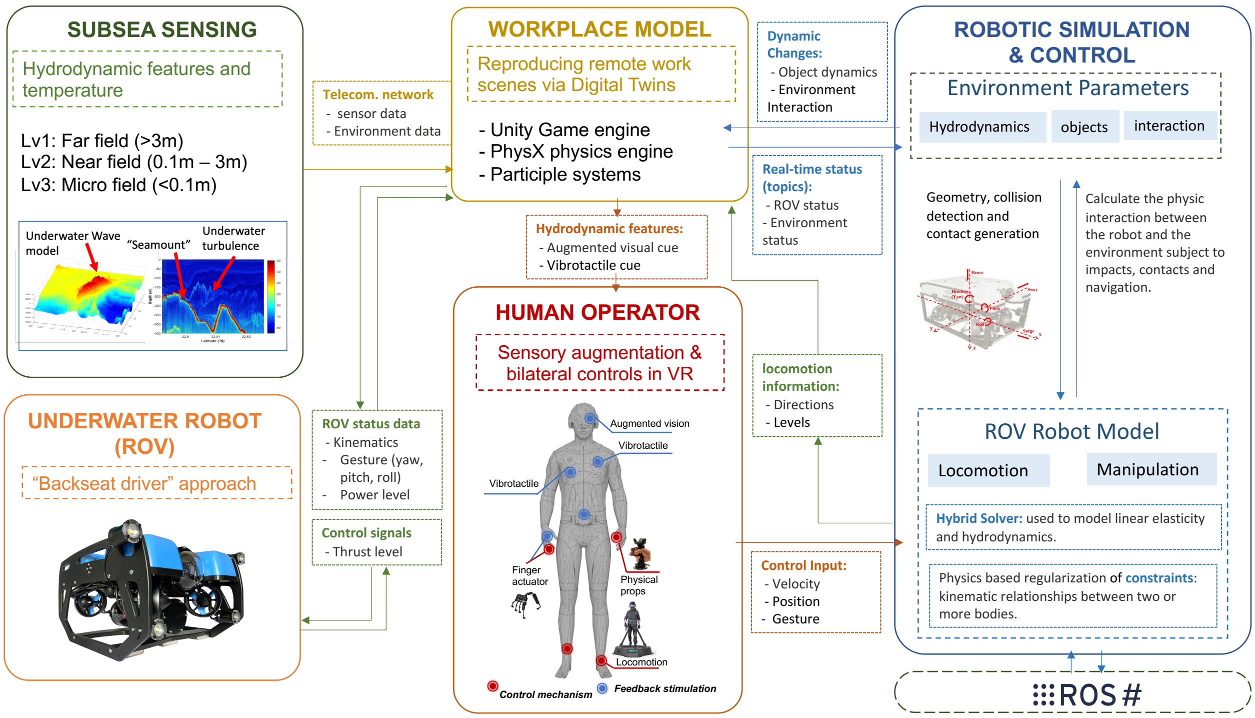


Fig.1: Proposed underwater human-robot interaction for enhanced ROV teleoperation.

- **Workplace Model Module:** The real-time sensor data is then used to model spatiotemporal dynamics of a subsea zone in the vicinity of the robot. To generate an immersive visualization of the subsea workplace, a game engine Unity v2020.1 [15] is used. Unity can model the far field sensor data as vectors and render the entire space as Virtual Reality displays. Another key feature of the proposed system is to convert the hydrodynamic features into human-perceivable sensations, i.e., vibrotactile cues. To realize this function, a physics game engine NIVIDIA PhysX is used (version 9.19) to simulate underwater [16]. Specially, the smoothed-particle hydrodynamics (SPH) particle method [17] of PhysX is used to simulate the hydrodynamic changes based on the sensor data. The raw data is used to determine the initial conditions of the particle emitters. Then a collision detection mechanism is used to examine the collision events between each particle and the virtual ROV model. The collisions frequency and magnitude will be used to generate haptics of different levels (see the next section)
- **Human Operator Module:** Although in ROV operations many of the environmental parameters can be collected and displayed via monitor screens, it requires a significant training effort to comprehend and react in a timely manner. To mitigate the perceptual-motor malfunction and reduce training needs, we use a virtual telepresence environment based on VR and a sensory augmentation simulator, or the human operator module. Two functions are built for human operator module including the sensory augmentation and the bilateral control. Below we introduce the method for sensory augmentation. Bilateral control will be described in the next section.

For sensory augmentation, hydrodynamic features are simulated as the visualized vectors via a virtual reality (VR) headset, and via and vibrotactile via a haptic suit. For the far field data, clusters of vectors are rendered to indicate the overall hydrodynamic flows necessary for the operator's navigation decision-making, including fluid directions, speed, and gradient extensions. Colored vectors are rendered in the simulation to indicate temperature changes. These clusters of vectors flash along with the direction the same as flow data, with amplitude and frequency indicating the flow speed. A more frequent swing and larger amplitude indicate faster and stronger water flows. Compared to traditional camera view feedback, VR provides more enriched spatial information with immersive and interactive visual feedback. Such a hierarchical system design can simplify the overall piloting effort during routine operations and reduce operation inaccuracy due to human errors. For the near field waterbody surrounding the ROV, a SPH particle system is applied to simulate the physical interactions with the ROV in a realistic way. In this study, Obi Fluid [18, 19] is selected as the core near field particle simulation method. The activated particle number is set to 650 for balancing the simulation fidelity and CPU cost. To simulate physical interactions between the waterbody and the ROV, seven particle emitters are set around the ROV model, as demonstrated in Fig. 2a. The initial parameters of these emitters, such as particle initial direction and speed, are based on the received hydrodynamic data from ROV pressure sensors. Whatever actions the human operator initiates would trigger the status changes to the emitters. For example, an emitter in front of the ROV model will generate a particle flow if operators perform a forward operation. A total of 40 sensors are deployed in the virtual ROV model (a digital replica of the real ROV) to collect the collision events between the particles and the ROV model (Fig2b). We use a dynamic collision detector, *PxParticleFlag::eCOLLISION_WITH_DYNAMIC*, to examine whether a particle collided with the dynamic rigid body (i.e., the virtual ROV model) during the last simulation step. Then two methods from PhysX are used to read position and velocity information, including *PxParticleReadDataFlag::ePOSITION_BUFFER* and *PxParticleReadDataFlag::eFLAGS_BUFFER*. The collected parameters are used to calculate the vibration magnitude of a haptic suit with the same number of vibrators (Fig.2c) using the following formula:

$$m_i = (e^{0.4F_{sensor}} - 1)/(e^{0.4F_{sensor}} + 1) + \ (h - h_{min})/2(h_{max} - h_{\min}) \qquad \text{...Eq(1)}$$

Where m_i refers to the magnitude of the i^{th} vibrator on the haptic suit, F_{sensor} represents the flow intensity sent by the sensors, h is the subsea depth of the ROV, h_{min} is the minimum subsea depth of workplace, and h_{max} is the maximum subsea depth of workplace. The subsea hydro pressure is converted into a range of 0 to 0.5, which ensures the final haptic suit vibration intensity would not be larger than 1.5cm/s^2. As such, the human operator can "see" and "feel" the real-time fluid changes analogous to what most fish are capable of.

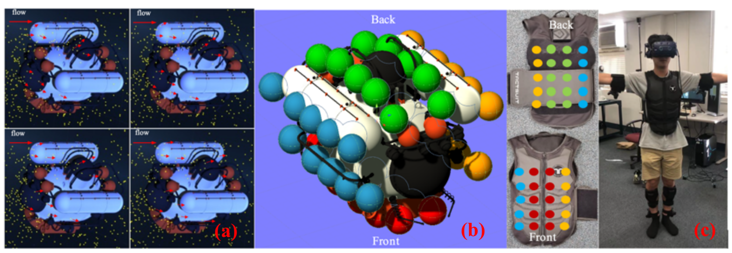


Fig.2: Simulating hydrodynamic features on human operator via a haptic suit

In addition to the reality reconstruction of the near water, we will also apply MS MRTK [20] (an augmented reality toolkit) to enhance color perception [21], such as highlighting the object boundaries, shapes and volumes that will help human operator concentrate on the work zone, and visualizing occluded objects (see-through effects). Although other subsea environmental features may also be relevant (such as salinity and turbidity), we will focus on the above three categories of information for a better system reliability. We will also examine sensory stimulation strategies for user adaptation: *Sensory Prioritization* to decide what feedback is most needed for a given situation; *Sensory Filtering* to determine what sensory feedback shall be blocked to avoid cognitive overload; and *Sensory Manipulation* to simulate one sense (e.g., force) in another form of sense (e.g., vision). Remote robots will be a natural extension of human senses.

- **Robotic Simulation and Control Module.** Physics engine simulation data and sensor data from the remote ROV need to be transferred to Robot Operating System (ROS) seamlessly to enable ROV simulation and controls. Building on our previous work [22], we will examine a data synchronization system for VR and robotic systems. The system features two functions: converting environmental parameters extracted from the workplace model (hydrodynamics, objects, and interactions) to ROS to rebuild the 3D scene in ROS Gazabo for robot simulation, and to enable the control commends for the ROV. Rosbridge is used to provide a JSON API for transferring data between ROS and Unity [23]. Rosbridge also provides a WebSocket server for web browsers to interact with, serving as a connecting between ROS and the network [23]. ROS server converts ROV dynamics data into JSON messages via rosbridge and publishes it to the website or receives JSON message from Internet and converts it to ROS message [23, 24]. On the Unity side, we use ROS#, a set of open-source software libraries in C#, for communicating with ROS from .NET applications, in particular, Unity [25]. ROS# establishes a WebSocket in Unity so that Unity can connect to a computer with a specific IP address through the network and transfer data. It also helps build nodes that publish and subscribe topics from ROS in Unity. ROS# converts data into

JSON and publishes it or converts the received data into the original format. We grant ROS server and Unity's WebSocket the same IP address, so that ROS server can publish the processed topics to the ROS platform, and the Unity can subscribe to all topics on ROS platforms through ROS#.

The robotic simulation and control module also supports an intuitive control of the remote ROV via natural body motions. As shown Fig.3. Human control input parameters, including local rotation of HTC trackers, body postures and a secondary auxiliary controller, are designed to match ROV control parameters such as rotation, moving and some specific control functions. The local rotation of human body is sent to ROV for pitch, roll and yaw control, which ensures ROV's orientation consistent with human's body motion. Human body postures are designed to control ROV moving in the subsea environment. For example, ROV pitch down when human operator leans forward. A secondary auxiliary control method, HTC VIVE controller is introduced for vertical up and down operations and function control. Specifically, the y axis input value of touchpad was used to control up and down for ROV, with the x axis value for speed control. The Boolean value of trigger button was designed to control the system on and off.

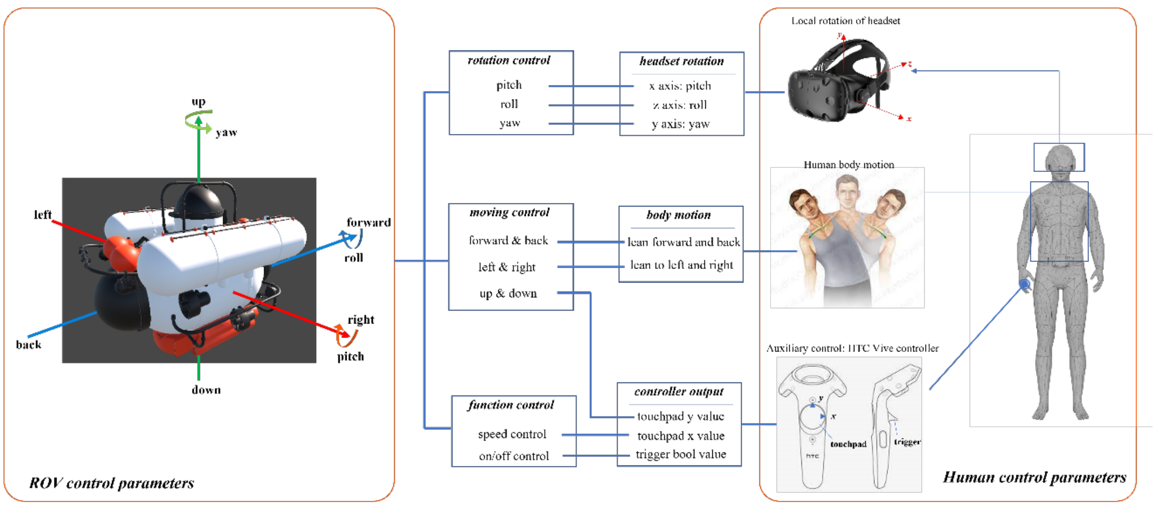


Fig.3: Natural body-motion control

Another need for seamless ROV teleoperation is to render the kinematics features of the remote ROV in VR (e.g., speed, gesture etc.). This is because the locomotion control signals from the human operator are not always realized on the remote ROV due to the dynamic subsea environment. For instance, a human operator may lean forward by 10 degrees to command the corresponding 10-degree negative pitch of the ROV. Nonetheless the real ROV may only demonstrate a 5-degree pitch due to the liquid viscosity underwater. As such, the reactions of the ROV kinematics must be regenerated despite what controls are given by the human operator. In our system, we don't rely on the real ROV kinematics data (collected from the onboard sensors) because of the possible tracking errors or telecommunication latencies. Instead, we rely on the real-time ROS Gazebo simulation to recover the predicted ROV kinematics status. The challenge would be to reproduce the robotic dynamics in ROS Gazebo in a precise and accurate manner. We will use a hybrid solver that solves both the linear elasticity and hydrodynamic changes of the simulated ROV in Gazebo, such as [26].

- **Subsea Robot (ROV) Module.** The last module of the proposed system is the remote ROV. The vehicle used in this project is based on a BlueROV2 platform with a heavy configuration. The BlueROV2 is an open-source underwater vehicle equipped with six thrusters in a vectored configuration. With the heavy retrofit kit, four additional vertical thrusters are added to the vehicle, providing the vehicle with all six degrees of freedom. The based vehicle is powered by an onboard 18Ah battery, giving 2-3 hours battery life with a single charge. On top of the base platform, our vehicle is upgraded with a Jetson Xavier NX backseat computer to perform high-level sensor fusion and closed-loop control autonomy. The vehicle is outfitted with a bottom-facing single-beam echosounder that measures distances with respect to the seafloor for up to 50 meters, a 360-degree scanning imaging sonar for underwater perception. In addition, the vehicle is equipped with a Nortek Doppler velocity log with current profiling capability that allows the vehicle to measure the relative velocity with respect to the seafloor as well as the far-field flow velocity for augmenting the operator's situational awareness in the digital-twin environment. We developed a "backseat driver" computing method to realize the open loop control needs. As discussed earlier, there may be a disconnection between the control commends issued by the human operator and the actual reaction of the ROV due to the changing hydrodynamic conditions in the subsea workplace. As a result, a resolver is used to generate the correct rendering of ROV kinematics in VR. The same applies to the controlling of the real ROV, as the real system also needs to match the control commends and mirror the behaviors in the VR environment. The same hybrid solver will be applied on the backseat driver computer.

DEMONSTRATION CASE

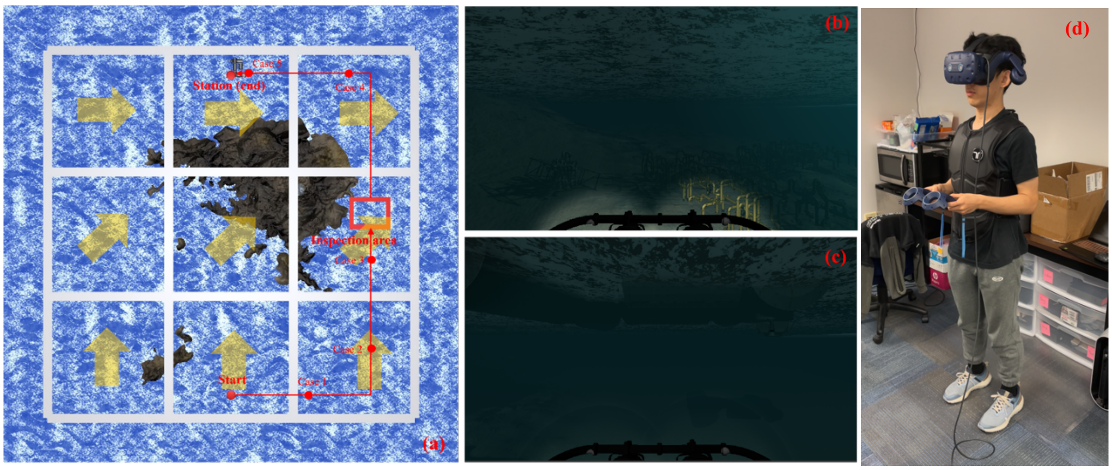


Fig.4: Demonstration case. (a) Task map; (b) Inspection area; (c) view of station; (d) Human operator with control devices.

We performed a test case to prove the concept. As shown in **Fig.4**, the operator needed to complete a subsea inspection in the inspection area then navigated to the station to end the task. The task route and ocean flow conditions are shown in **Fig. 4a**. In this task, operators could finish a series of basic operations including moving forward, up, down and turning around. With the combination of different flow conditions and ROV operations, the haptic suit would generate significantly different vibration patterns on the body of the operator. In total, five different representative cases were selected to show the varying haptic patterns, including right flow with forward operation (case 1), back flow with forward operation (case 2), 45-degree back flow with forward operation (case 3), forward flow with forward operation (case 4), and forward flow with up operation (case 5).

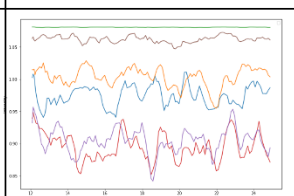
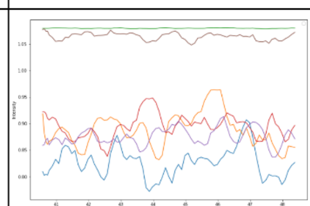
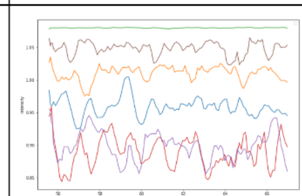
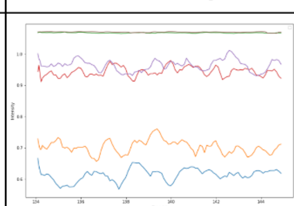
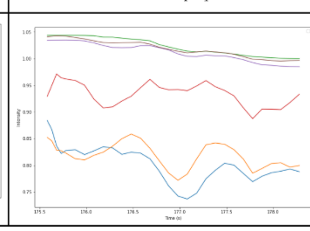
Flow condition	right flow & forward operation	back flow & forward operation	45 degree flow & forward operation
Intensity value			
Flow condition	forward flow & forward operation	forward flow & up operation	back_upper body back_middle back_lower body front_upper body front_middle front_lower body
Intensity value			

Fig.5: Haptic intensity pattern for five cases

Fig. 5 demonstrates the different haptic patterns of average intensity value in each case. For different combinations of flow conditions and operations, significant difference could be observed in the haptic feedback. For example, for the back flow with forward operation, a higher haptic intensity was observed in the front part. The reason might be that moving operation influence more than the fluid speed we set. For forward flow with forward operation, a similar higher haptic intensity patten was observed in the front part, but the difference between front and back is much greater. For forward flow with up operation, a general higher intensity was observed in the front and upper channels. The result showed that there was a significant difference in vibration patterns for different operations and flow conditions. By transferring underwater hydrodynamic conditions to human body sensation, participants could identify different ROV positions and locomotion conditions effectively.

DISCUSSION

1. Opportunities

We expect this new method of ROV teleoperations to advance a booming subsea engineering industry that requires a strong integration between human intelligence and robots to tackle environmental complexity (e.g., volatile water flow) and task dynamics (e.g., navigation with low visibility). At present, the needs for subsea robots are diverse, from inspection ROVs (smaller scale and single-purposed) to workhorse ROVs (bigger scale and versatile) for shallow water and deep-sea activities. Without losing the generalizability, this method is expected to enable a much closer human-ROV collaboration for subsea inspection and survey, i.e., the maneuver and navigation controls of remote ROVs for sensor data collection and scanning of vessels and subsea structure inspection in offshore zones. It can make the key tasks easier, including *navigation* (localization and state estimation), *control* (path planning and maneuvering through complex environments) and *perception* (for robot position control and the inspection task). Subsea inspection and survey are among the most common subsea robotic operations. The relevant tasks include but are not limited to subsea infrastructure inspection, geological survey, marine habitat monitoring, pollution assessments, ship-hull inspections, unexploded ordnance (UXO) surveys, contraband detection, aquaculture monitoring facility inspection, search and rescue, and archaeology exploration and surveys. Applications in other industries where the same technologies apply include hydro power-dam wall inspections, blockage detection at penstock intake, bridge and pier structure monitoring, nuclear plant inspection and operations, and survey and monitoring in lake environments. Subsea robotic inspection is urgently needed and represents unique challenges in both workplaces (diverse underwater environments) and works (dynamic and instant decision making, path planning, operational and decisional uncertainties).

This research is strongly positioned for better accessibly and inclusion because it aims to lower the career barrier for a traditionally highly professional area. The proposed underwater human-robot interaction approach will greatly simplify the requirement on engineering, science, and robotics knowledge for subsea engineering and underwater robot operation jobs. The marine and offshore sectors are dominated by male workers. The new job opportunities will help ease the inequality in gender, with that more women will feel more welcomed because of the safer work environment created by the virtual telepresence technology. The current subsea engineering also poses strict requirements on age, because of the mental and physical load in certain tasks. The sensory augmentation method for robotic control will mitigate the age requirement, promoting career longevity. The new technology will also help salvage the careers of experienced workers who have suffered from career injuries, such as diving diseases. Furthermore, because our investigation will focus on reskilling and upskilling the workforce that is threatened by automation, lessons learned in this project will help workforce transformation and secure job opportunities for US workforces in various industries. It includes construction and mining industries that have been dominant by underrepresented groups of workers.

We also anticipate potential economic impacts of our technology. We predict that the new technology will reduce costs through four channels: (i) Reduced training requirements. Current ROV operation and commercial diving are skill-intensive, with higher barriers to entry and expensive training[27, 28]. We expect the new technology to reduce these barriers. This reduces costs by reducing training time, expenses, and salary requirements for high skilled workers. (ii) Increased capital productivity. Currently, sub-sea inspections and maintenance are performed by the personnel onboard (POB), which carries high logistical, transportation, safety, and compensation costs – if operators can direct an ROV from a VR suit in an office park, rather than helicoptering out to a ship or platform, cost savings may be significant[29]. (iii) Increased capital utilization. Industry feedback (pilot interviews with three ROV service providers) indicates that ROVs may be used on only 50% of days because of the limited availability of high-skill, trained operators – this is unusually low[30]. Reducing operator training and reducing the costs of matching an operator with the robot can allow each piece of equipment to sit unused less often, lowering costs. (iv) Investment incentives. Reallocating human-performed tasks to HRC is especially incentivized in the low interest rate environment that long-run yields predict will characterize the next several decades, because capital costs for robots are amortized over years. Our plan for estimating industry growth is described as follows.

2. Challenges

There are still many challenges for us to resolve to make this technology viable. The first challenge relates to the technological maturity. Realizing the proposed system would require a significant change to the current ROV designs. It includes equipping the ROV systems with new sensors that can collect high-fidelity underwater environment data, such as pressure sensors on the surface of ROV and Doppler sensors for far field hydrodynamic sensing. The initial cost may become a burden for many businesses. A new data and telecommunication infrastructure is also needed for transferring the potentially big amount of data to support the human-robot sensory transfer. Without concrete evidence on the benefits of the proposed method, it would be extremely difficult for industry and academia to make the aggressive move in transforming the current systems.

In addition, we recognize that the technology innovation alone would not be sufficient for attracting the current and future maritime workforce to enter the new subsea engineering robot teleoperation sector. The lack of trust issue has been seen in many new technology adoptions. The workforce technology transformation cannot be capitalized without appropriate training and commitment. The training program needs to be integrated into the current training protocols to gradually adapt and change the transformative workforce. But there are many unknowns. First, we don't know how and to what extent a new ROV teleoperation experience affects productivity and safety for subsea robot operations. We expect that the introduction of the new human-robot interaction will inevitably result in behavioral and psychological changes of future underwater robot operators. Evidence must be collected to verify the benefits of the proposed technology, and more importantly, the possible side effects. Previous HRC literature has observed undesired side effects of introducing shared autonomy in workplaces, such as bully behaviors [31-33], distrust [34-37], loss of self-confidence in tasks [38-40], and loss of situational awareness [41, 42]. Traditional subsea inspection is among one of the most dangerous occupations [43, 44]. We don't know if the proposed HRI technology can enforce the required safety protocols in subsea inspection. Second, even given the productivity and training benefits attributed to the proposed new HRI technology, we still don't know if it is enough to increase the willingness for workforces from other declining industries to enter a subsea career. Considerations for changing career path can be complex. According to the Rhodes and Doering Model [45], factors include traits, demographic factors, human capital (e.g., education and occupational tenure), job satisfaction, motivation, organizational factors, and self-identification. We need to measure the career change motivation in addition to work performance. Third, we don't know how the proposed technology affects the training and education for a transformative workforce. Successful adult learning involves a complex process of transformation in perspective that is deeply tied to context and influenced by a catalyzing dilemma [46]. Findings from prior research indicates the importance of individual agency, shared experience, critical reflection, and the need for time [47]. However, little attention has been given to understanding how the unique attributes of a more applied professional setting might serve as an affordance [48]. Few studies have explored how a general transformative learning principle can be informed for the unique attributes of participants from diverse backgrounds, cultures, etc., or how emerging technologies might influence the processes and outcomes [49]. Especially, later stage adults are understudied, yet this segment is growing more rapidly than any other age group. There is a critical need for in-depth analysis of multiple theoretical perspectives of transformative learning, particularly involving comparative analysis. Applying various theoretical orientations for transformative learning to a context involving VR and HRI as an emerging technology would offer the opportunity to better understand both the nature and practice of a workforce transformation.

CONCLUSION

Subsea engineering operations heavily rely on ROV, and the performance depends on the seamless interaction between ROV and the human operator. Due to the dynamics of subsea environments such as the uncertainty of turbulence, affected visibility, and the interference with subsea ecosystems, control of subsea ROV is challenging for human operators who have never exposed to such an environment. Even with the tremendous amount of practice, the human operator can easily misjudge the situation and make wrong decisions in subsea operations. This paper introduces the basic information of a proposed human-robot collaboration method based on a VR and haptic simulation system. To explore the potentials of utilizing VR to accomplish ROV control, a haptic suit is combined with VR goggles to bring an immersive subsea environment to the operator. A comprehensive physics model is first transferred to VR equipment, depicting a detailed underwater environment including turbulence and interaction with ambient objects. Then the haptic suit executes the corresponding pressure signals to the operator's body in real-time. The feedback signals from haptic suit provide the human operator with realistic sensation of subsea situations peripheral to the robot. This immersive virtual environment ensures ROV operators of real-time awareness of the proximity conditions and prediction of changes. As a result, a less-trained human operator can pilot the ROV based on his/her intuition and experience to maximize the performance and avoid potential mistakes. A variety of opportunities have been identified, including supporting the easier underwater inspection tasks, improve the access and inclusion of subsea engineering, and the long-term economic benefits. The challenges related to technological transformation and training/adoption issues have also been identified.

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